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THRUST EFFECTS ON MISSILE AERODYNAMICS

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Problems arising from rocket plume effects on missile aerodynamics are generally discussed. The approach taken to investigate these problems is outlined and preliminary results are presented.

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ABSTRACT

Problems arising from rocket plume effects on missile aerodynamics are generally discussed. The approach taken to investigate these problems is outlined and preliminary results are presented.

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SYMBOLS

A	Body reference area $= \frac{\pi D^2}{4}$
A_j	Area at exit plane of nozzle
C_T	Thrust force coefficient $= \frac{\text{thrust}}{q_\infty A} = \frac{2A_j}{A} \frac{p_j/p_\infty\left(\gamma_j M_j^2 + 1\right) - 1}{\gamma_\infty M_\infty^2}$
D	Body diameter = 2.5 in.
D_B	Base diameter
D_N/D_B	Nozzle exit to base diameter ratio
L_N	Length of nozzle from throat
M_j	Design jet Mach number at exit plane of nozzle
M_∞	Free-stream Mach number
p	Local body static pressure
p_b	Base pressure
p_c	Nozzle chamber pressure
p_j	Jet static pressure
p_{sep}/p_∞	Pressure ratio inducing separation
p_1	Static pressure at orifice located 0.225D ahead of body base
p_∞	Free-stream static pressure
q_∞	Free-stream dynamic pressure
R	Body radius at model base
r	Radial distance from model centerline of pressure orifices on model base
X	Longitudinal distance from base

X_p	Longitudinal position of normal jet simulator aft of model base
	Angle of attack, degrees
γ_j	Ratio of specific heats for jet flow (γ for air = 1.4)
γ_∞	Ratio of specific heats for free-stream flow (γ for air = 1.4)
Δc_p	Local loading coefficient on body vertical centerline plane
$\frac{\Delta p_1}{p_\infty}$	Pressure rise at $\frac{X}{D}$ = 0.225 due to increasing C_T
θ_N	Nozzle exit half-angle, degrees

1. Introduction

The capability of rocket motors to produce very high levels of thrust within a given cross-sectional area has introduced various missile aerodynamic problems. These problems are associated with effects of the large (on the order of 1.5 to 2.0 missile diameters) jet plume on the flow immediately ahead of the missile base. In this region, either flow separation or change in the flow field can result in catastrophic pitch up or loss in accuracy of missiles because of loss in stability (Figure 1), or degradation of control effectiveness. Other effects that can occur are excessive control hinge moments, loss in roll rate, unsymmetrical lift forces, and hysteresis in the variation of aerodynamic forces and moments with angle of attack.

Previous research into jet plume effects on missile aerodynamics [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] has been concentrated on supersonic, high altitude flight. In this environment, a very large plume is apparent and detrimental effects such as flow separation do not come as a complete surprise to the missile designer.

For missiles with moderately high accelerations, launched from either stationary points or subsonic aircraft, detrimental plume effects may occur even at low altitudes. In these cases, adverse plume effects are not as noticeable as on missiles or aircraft flying at high altitudes. For missiles of moderate acceleration at low altitude, adverse plume effects first occur at a narrow speed range centered around a Mach number of 1. With increasing thrust (or acceleration) and altitude, the effects spread progressively over the entire Mach number range. At lower values of acceleration, it is possible for a missile to pass through the critical speed range in a very short time. In this case, the adverse effect of the plume on missile aerodynamics may never be noticed unless there is some unexplained degradation in accuracy or some quirk in the missile flight path. These effects are not picked up in the standard wind tunnel definition tests and may not be determined until the latter phases of missile development. For this reason, it is important to be able to predict when undesirable plume effects will occur.

Because of the importance of the problems associated with jet plumes to future missiles, a research program has been established by the Army Missile Command. To date several exploratory wind tunnel tests have been conducted. Results of these tests and a thorough assessment of the problem areas have led to a research plan which includes:

a) Development of methods that will indicate the conditions where the problem of plume-induced aerodynamic effects on missiles will probably occur

b) Development of wind tunnel test techniques which adequately simulate high thrust effects on aerodynamic stability

c) Development of techniques which will allow missile designer to avoid problem areas, and where this is not possible, development of means of alleviating undesirable aerodynamic effects.

2. Development of Plume Effects Indicators

Past research at the Army Missile Command suggests the possibility of using base pressure p_b/p_∞ as an indicator for the onset of undesirable plume effects. The characteristics of base pressure variation with thrust are summarized in Figure 2. The base pressure [11] at various Mach numbers, nozzle diameters, and chamber pressures can be correlated as a function of the thrust force coefficient (C_T). A correlation of experimental data for a configuration with the following characteristics is presented in Figure 2:

a) A cylindrical afterbody

b) Cold air nozzle flow

c) Nozzle flush with base

d) Nozzles of various diameters with a design Mach number of 2.7 and a conical expansion half angle θ_N of 20 degrees.

Although the correlation is based on experimental results for cold air nozzle flow, there is close agreement with flight test results for configurations with cylindrical afterbodies, with solid propellant rockets of moderate specific impulse, and with the nozzle flush with the body base. There is also good agreement with the values of p_b/p_∞ predicted by the flow model of Korst, et al [12] as modified by Addy [13]. (For higher impulse rockets there is a discrepancy which will be discussed later.)

To use Figure 2 for estimates, C_T is calculated for conditions at a given free-stream Mach number. The base pressure is then determined from the proper free-stream Mach number curve for the calculated C_T. For example, for a free-stream Mach number of 1.0, the base pressure for C_T values between 0.01 and 1.8 are along the broken line (1) to (2). For C_T values between about 1.8 and 15.0, the base pressures fall on the solid line (2) to (3) which is common to all free-stream Mach numbers. For C_T values above 15.0, the base pressures fall on the broken line (3) to (4). The base pressures on the line (3) to (4) are sufficient to cause extreme thickening or even separation of the body boundary layer. The variation of p_b/p_∞ with C_T at the higher values of C_T are shown in more detail in Figure 3. These data were taken from reports [14, 15] on a model having a sonic nozzle with a jet-to-base diameter ratio of 0.45. With increasing C_T, the base pressure for each free-stream Mach number approaches a separate plateau pressure. For $M_\infty > 1.5$ plateau base pressures are compared to the plateau pressures of Zukoski [16]. Zukoski has also proposed an approximate empirical turbulent boundary layer separation criterion in the simple form

$$\frac{p_{sep}}{p_\infty} = 1 + 0.365\, M_\infty \quad .$$

The separation pressure predicted by this criterion is shown in Figure 3.

An indication of the onset of adverse plume effects can also be obtained from changes in body surface static pressures with increasing thrust. The value of C_T, where a significant increase (arbitrarily chosen as when $\Delta p_1/p_\infty = 0.1$) in body pressure occurs, is shown in Figure 3. This value of C_T is obtained from Figure 4 which shows the variation with C_T of the pressure from a selected orifice. (The orifice chosen was located 0.225 body diameters ahead of the base. Orifice locations nearer the base are affected by the base pressure being transmitted upstream through the boundary layer.) The variation of pressure with C_T is characterized by a steep increase in pressure to a plateau pressure for the higher Mach numbers. With decreasing Mach number the rate of increase and the plateau pressure decreases. For Mach numbers of one and less a different shape of curve is apparent. Although the curves in Figure 4 are obtained from one orifice at various values of C_T, these curves are representative of the pressure distribution along the body for a specific value of C_T. The pressure distributions at supersonic speeds are typical of the normalized pressure profiles for supersonic turbulent separated flow [16]. The distributions for Mach numbers of one or less exhibit altogether different characteristics than for supersonic speeds. Since no abrupt pressure rise is evident, there is some doubt as to whether boundary separation occurs in this case at sonic or lower velocities. However, regardless of whether or not separation occurs, the effect on missile aerodynamics is the same for subsonic and supersonic speeds [17].

Referring to Figure 3, the two schemes for predicting the onset of undesirable aerodynamic characteristics are not in agreement at the higher Mach numbers and Zukoski's technique is not applicable for subsonic velocities. Probably a good compromise would be to use the inflection point of the curve for each free-stream Mach number. However, for the present, it appears that little can be gained by tying down the exact point on the curve where plume effects occur because of the lack of reliability of obtaining accurate values of base pressure in this region.

Neither analytical nor empirical techniques for estimating base pressure are currently applicable in this region. Therefore, the only easily available source of base pressure data in this region is wind tunnel tests using air or other cold gases to simulate the jet. However, results from these tests do not agree with data from rockets, especially liquid rockets of high specific impulse. A comparison between estimated values of p_b/p_∞ and values obtained from unpublished missile flight and wind tunnel tests of an Army missile is shown in Figure 5 The majority of the test values of p_b/p_∞ are between 20 and 30 percent higher than predicted values. A possible explanation for the discrepancy between experiment and estimate is the phenomenon called afterburning which tends to increase base pressure.

3. Development of Wind Tunnel Test Techniques

A difficult problem is the simulation of jet plume effects on the aerodynamic stability of specific missile configurations during experimental investigations. Although cold gases (such as air) do not exactly simulate the rocket plume, the use of these gases gives the correct trends and considerably reduces the complexity of testing. However, the use of cold gases still poses a problem. For example, a large mass flow is required to simulate an axial jet with sufficient momentum to cause adverse aerodynamic effects. Therefore, a duct having a large cross-sectional area is necessary to supply high-pressure air (or other gases) to the model. This condition rules out the use of sting-supported models for axial thrust force simulation.

The approach taken has been to use a strut-mounted model with axial jets to investigate zero or small angle-of-attack effects of the jet plume and to explore various means of simulating axial jet plumes. A standard configuration for comparison has been chosen as an air jet with an exit Mach number of 2.7, a nozzle exit angle of 20 degrees, an exit to base diameter ratio of 0.8, and a cylindrical afterbody. This configuration has been tested at various free-stream Mach numbers, jet chamber pressures, and angles of attack. Pressure measurements were made at a meridian along the body upper surface (opposite support strut) and on the model base. A sketch of the standard strut supported configuration is shown in Figure 6.

The effect of varying nozzle chamber pressure on base and body pressure distribution at zero angle of attack is shown in Figure 7a and b. The pressure distribution in Figure 7a is typical for free-stream Mach numbers of one or less. The sharper pressure rise apparent in Figure 7b is typical for free-stream velocities above sonic velocity.

The effect of angle of attack on body pressure distribution at a constant jet chamber pressure is shown in Figure 8a and b. The crossover in the pressure distribution about one-half caliber ahead of the body base was not expected and to the authors' knowledge is the first time this phenomenon has been shown experimentally. Assuming the data at negative angles of attack represent the lower surface at positive angles of attack, the differences in pressure can be considered as being proportional to the afterbody loading distribution at a positive angle of attack. Using this assumption, Figure 9 has been prepared to show the loading on the vertical centerline plane representing an angle of attack of 2 degrees for various levels of thrust. For the higher thrust levels, the positive loading aft of the crossover point is stabilizing, whereas the negative loading ahead of the crossover point is destabilizing. It appears the load distribution may be influenced by the model strut shown in Figure 6. Therefore, to clarify thrust effects on stability, the differences in loading between jet on and jet off are shown in Figure 10.

Several types of plume simulators have been investigated. Cones, discs, and 12 small normal jets situated behind the model base have been used as plume simulators on sting-mounted force models [17]. Plume simulators tested in conjunction with a strut-mounted pressure-distribution model include discs, shaped solid plumes, solid plume with the outside 20 percent of the mass flow simulated by an annular air jet, and 24 small normal air jets issuing from a chamber aft of the model base [18]. No conclusions have been reached concerning the more promising types of simulators for further development.

The selection of the appropriate type of simulator for a particular investigation will probably depend on the object of the investigation. One advantage of discs and normal jets is that various levels of thrust can be simulated without a change in the physical configuration. Typical pressure distributions using the normal jet simulator are shown in Figure 11a and b.

4. Missile Design Techniques

Although little understanding exists of the flow mechanism involved in adverse plume effects, certain trends from exploratory investigations that tend to alleviate the problem are apparent. Any parameter that tends to increase base pressure (such as increasing C_T) tend to increase the likelihood of plume effects. Based on experimentally determined high-thrust base-pressure characteristics and the separation criterion of Zukoski [16], a chart has been prepared which shows the flight environment where jet plume effects are important for a typical missile configuration (Figure 12). The variation of the critical ratio of thrust to missile cross-sectional area with Mach number is shown in Figure 10 for three different altitudes. Values of thrust to cross-sectional area on a particular curve indicate the approximate onset of adverse plume effects or increasing probability of adverse effects occurring. Since the value of thrust to cross-sectional area is a measure of missile longitudinal acceleration, adverse effects can be avoided by reducing acceleration. If average acceleration cannot be reduced, it is possible to have a progressive (or ramped thrust) so that the highest thrust occurs at the highest Mach number. Since missile cross-sectional area is a parameter affecting C_T (and indirectly base pressure), some design control of plume effects can be obtained by lowering missile fineness ratio.

Adverse plume effects on missile aerodynamics can also be delayed by changing the geometry of the missile afterbody or nozzle. The effect of nozzle shaping on base pressure is illustrated in Figure 13. The difference in base pressure variation with C_T for a sonic nozzle and a nozzle with the same throat diameter designed to have uniform flow, an exit Mach number M_j of 2.7, and a nozzle exit to base diameter ratio D_N/D_B of 0.8 is shown. At the maximum value of C_T shown in Figure 13, the external jet boundary for the sonic nozzle initially expands to an angle of approximately 65 degrees. Consequently, a large part of the jet momentum is in a radial direction resulting in a very high base pressure indicating adverse plume effects. For the long nozzle at the same thrust, the initial jet expansion is approximately 25 degrees but most of the jet momentum has been directed in the axial direction by the time it reaches the nozzle exit.

The curve for the long nozzle can be shifted to generally match the sonic nozzle data by dividing the value of C_T by a factor of 9. If data for the long nozzle can be extrapolated to higher values of C_T by using the sonic nozzle data as a guide, it is reasonable to assume that a value of C_T above 150 can be attained without adverse plume effects.

The two nozzles chosen are extreme cases for the purpose of illustration. The optimum nozzle would be some design between the two extremes. It is apparent that reduction of the severity of plume effects by change in nozzle geometry can be achieved only through an increase in missile length and nozzle weight. Therefore, a design tradeoff must be reached between missile weight and length against the degree of adverse plume effects to be tolerated.

An indication of the effect of nozzle length on delaying adverse plume effects is shown in Figure 14. In addition to the data for the sonic nozzle and uniform flow nozzle shown in Figure 13, base pressure data from two conical nozzles with the same throat area and a jet Mach number of 2.7 [14] are used for comparison. The same procedure used in Figure 13 to shift the uniform flow nozzle data to fit the sonic nozzle data was used for the conical nozzle data using a value of $p_b/p_\infty = 1.55$ as an indication of the onset of adverse plume effects (Figure 3) for a free-stream Mach number of 1.5. Values of critical C_T were obtained for each nozzle.

Another design tradeoff possible is the variation of missile afterbody external shape. The effect of various levels of thrust on the base and afterbody pressures for typical flared and boattail afterbodies [19] is presented in Figures 15 and 16. By comparing these figures with the cylindrical data of Figure 7b on the basis of C_T, it is apparent the boattail is more susceptible to adverse plume effects than the cylindrical afterbody while the flared afterbody is less susceptible than the cylindrical afterbody. A comparison of the variation of critical C_T with Mach number at sea level between the cylindrical afterbody (repeated from Figure 9) and boattailed and flared afterbodies is shown in Figure 17.

5. Conclusions

Significant progress has been made in a research program investigating thrust effects on missile aerodynamics. Several critical parameters have been identified, trends established, and a research plan for further investigations has been formulated. The trend toward higher accelerating missiles increases the likelihood of encountering detrimental plume induced aerodynamic problems.

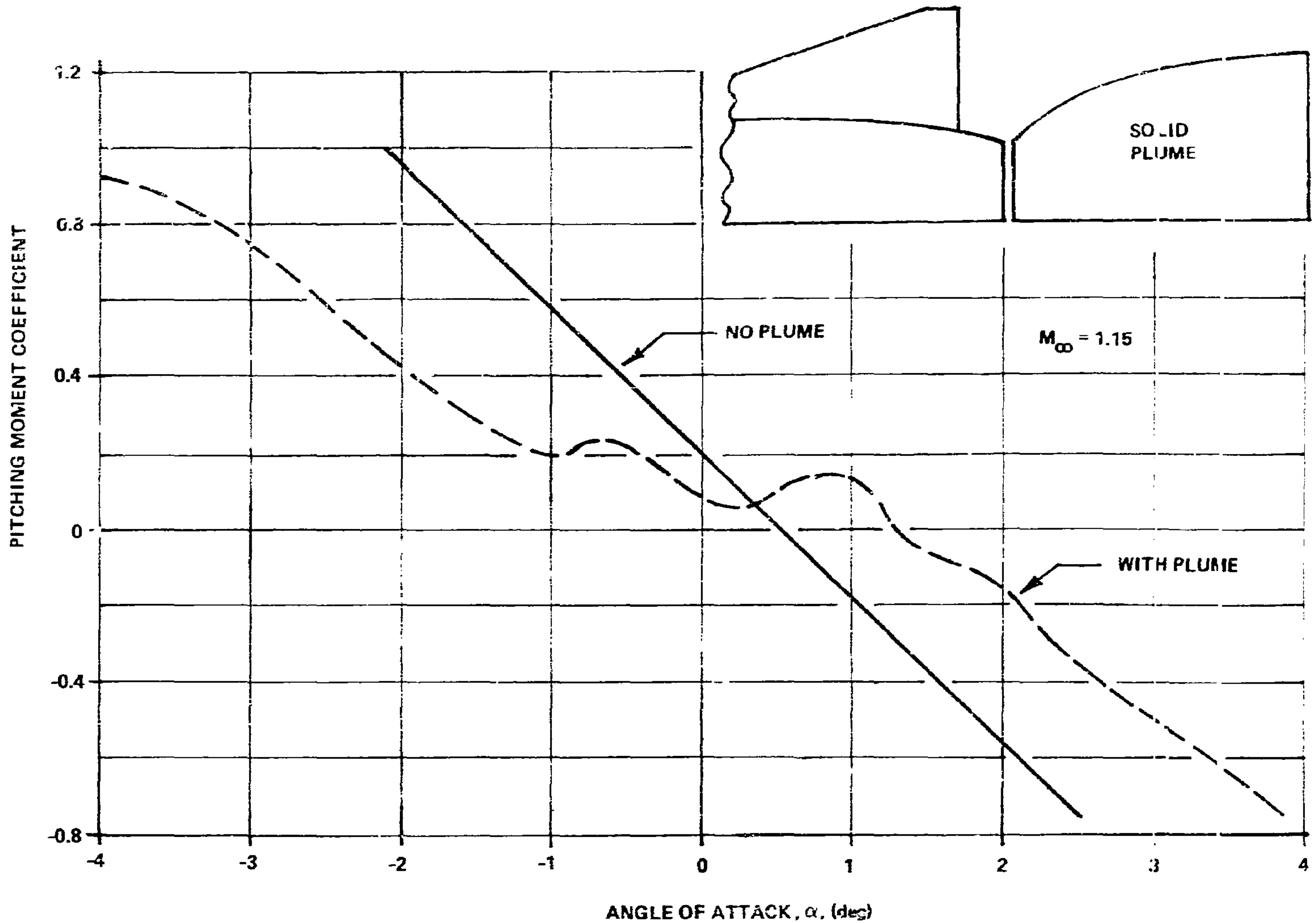


Figure 1. Effect of Simulated Plume on Missile Stability

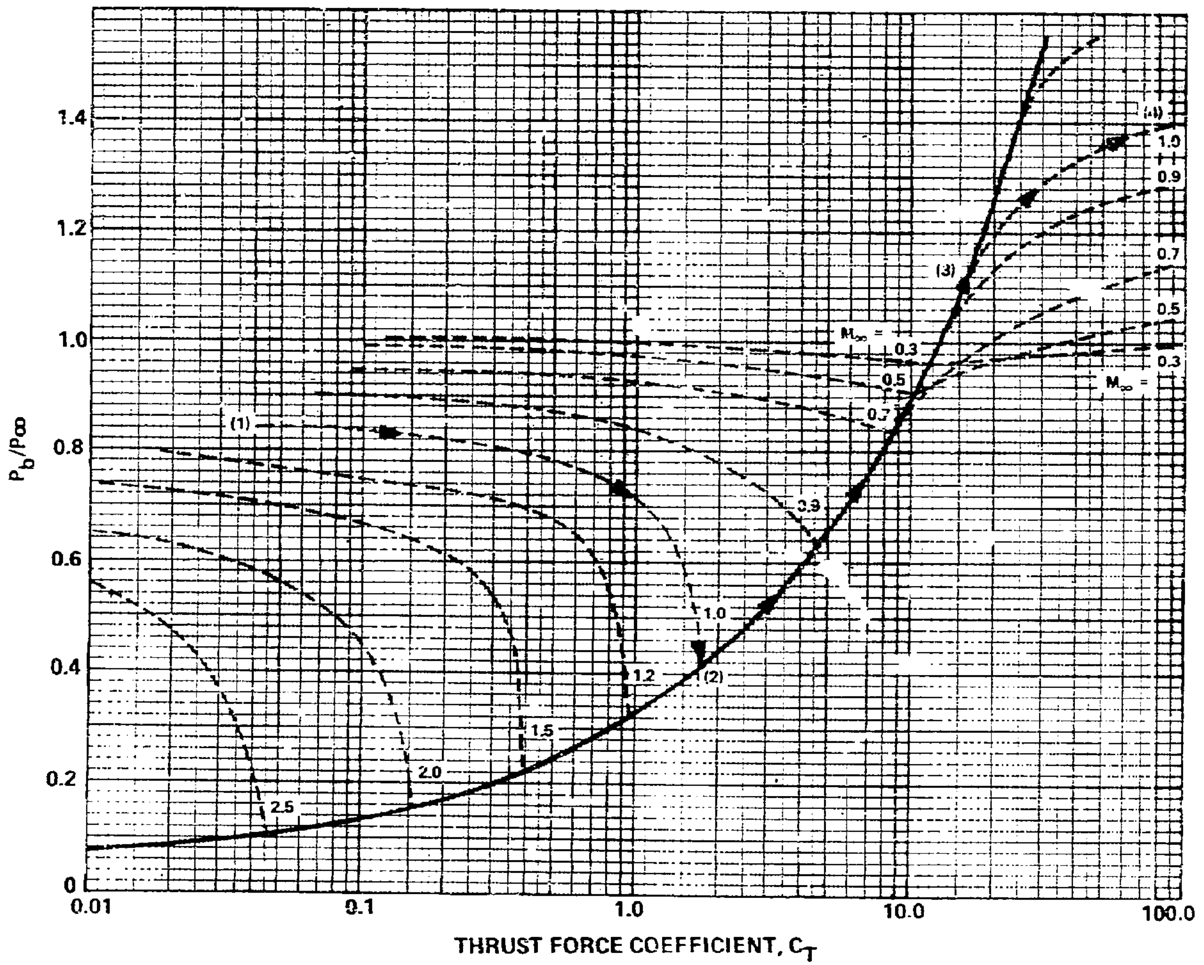


Figure 2. Base Pressure Variation with Thrust for a Cylindrical Afterbody with a Nozzle Flush with Base, Cold Air, $M_j = 2.7$, $\theta_N = 20$ deg

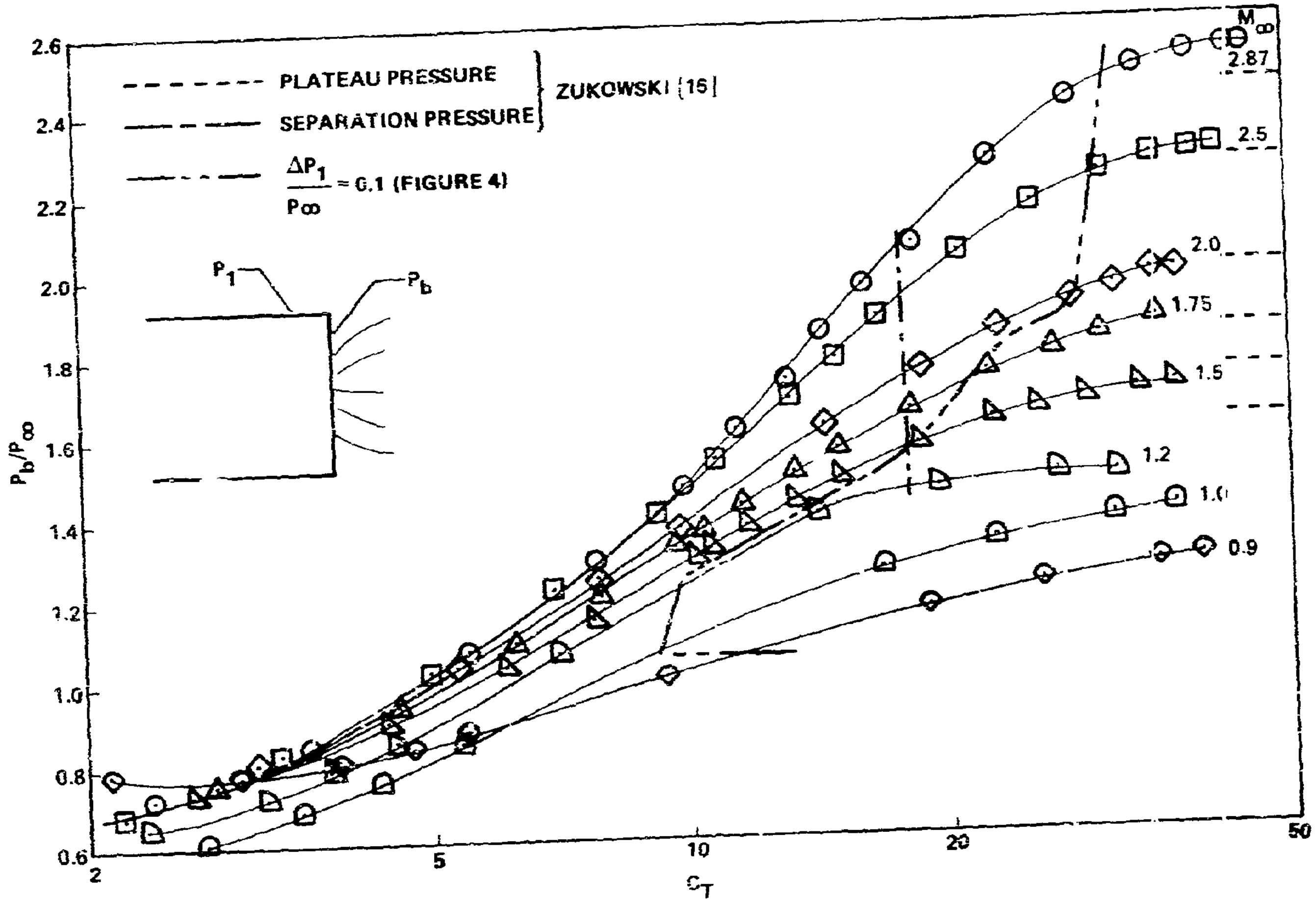


Figure 3. Base Pressure Characteristics at Thrust Levels Sufficient to Affect Missile Aerodynamics, Sonic nozzle, $D_N/D_B = 0.45$, Cylindrical Afterbody

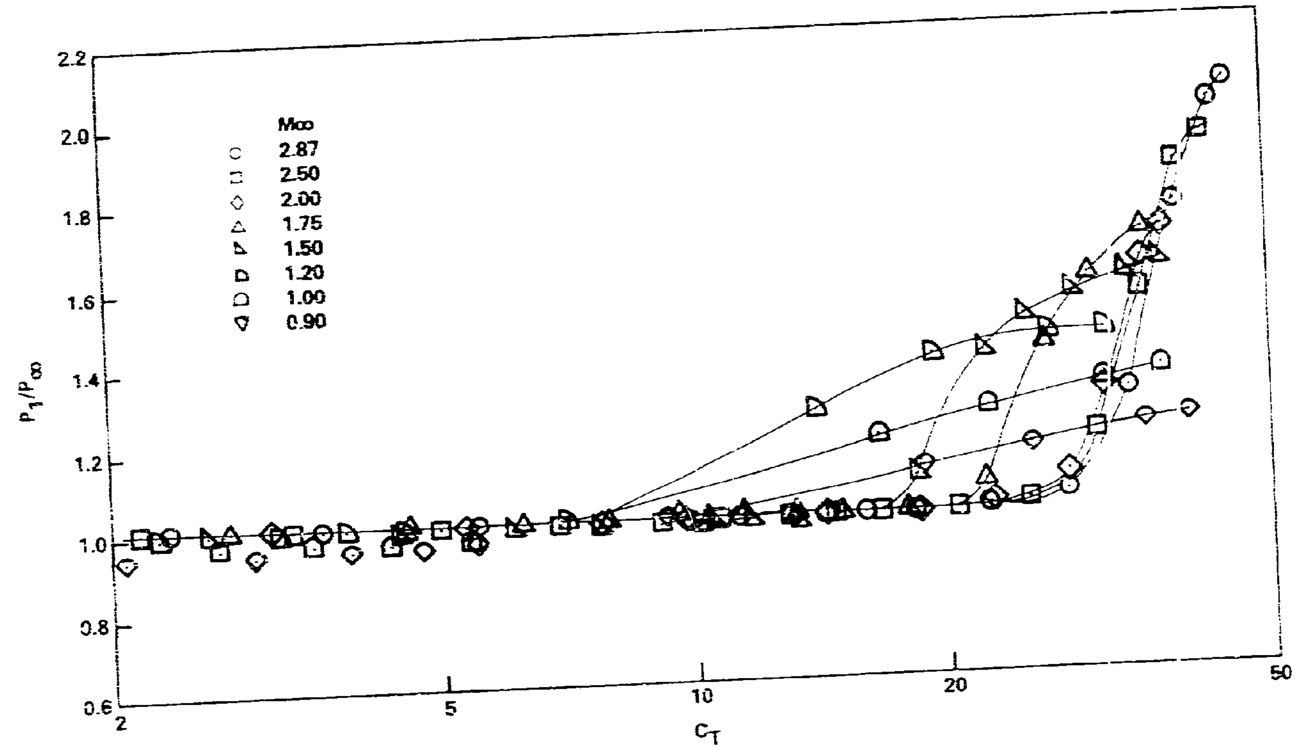


Figure 4. Effect of Thrust on Body Pressure $X/D = 0.225$, Cylindrical Afterbody.
Sonic Nozzle, $D_N/D_B = 0.45$

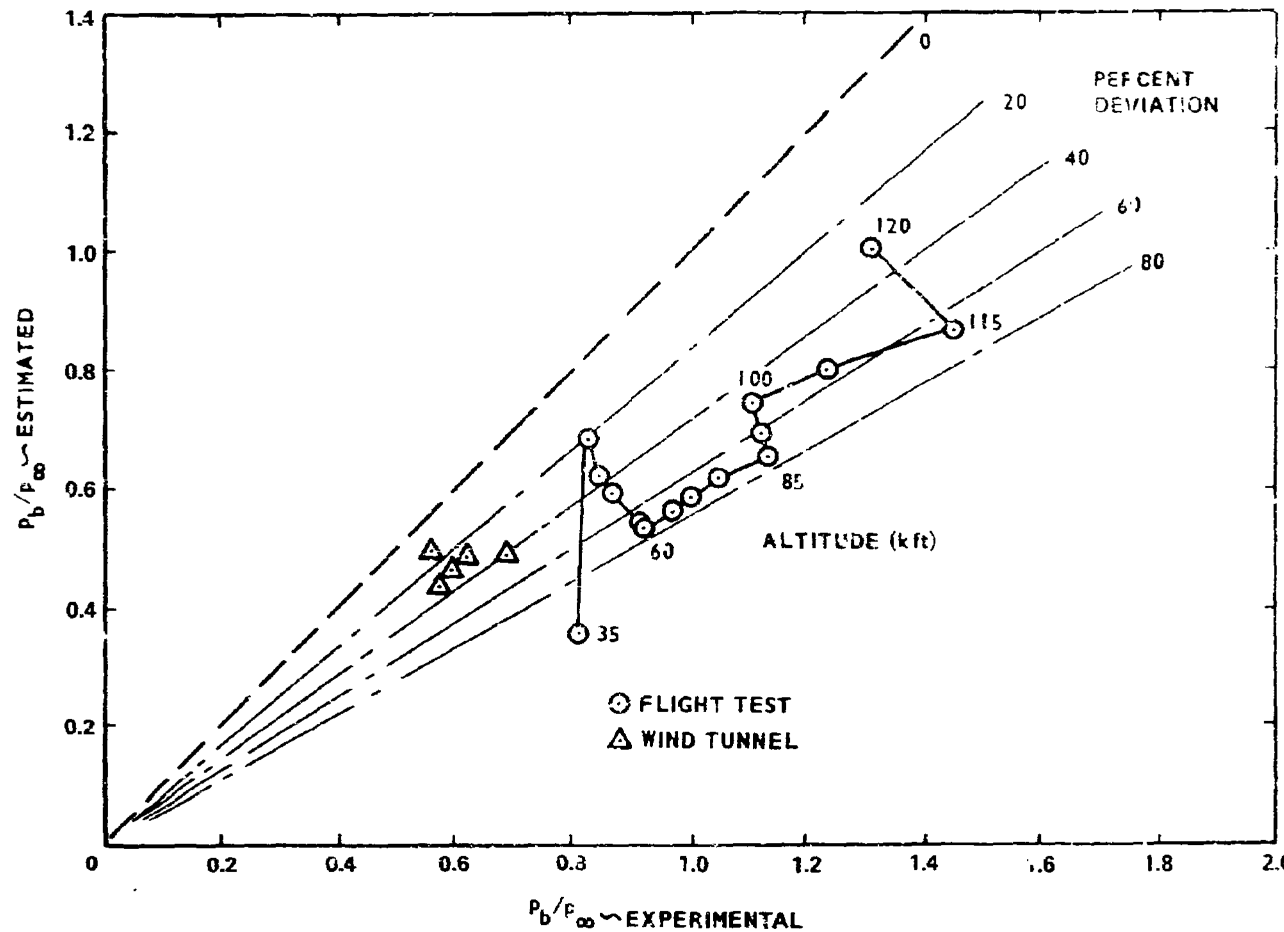


Figure 5. Comparison of Estimated with Experimental Values of Base Pressure for Hot Exhaust

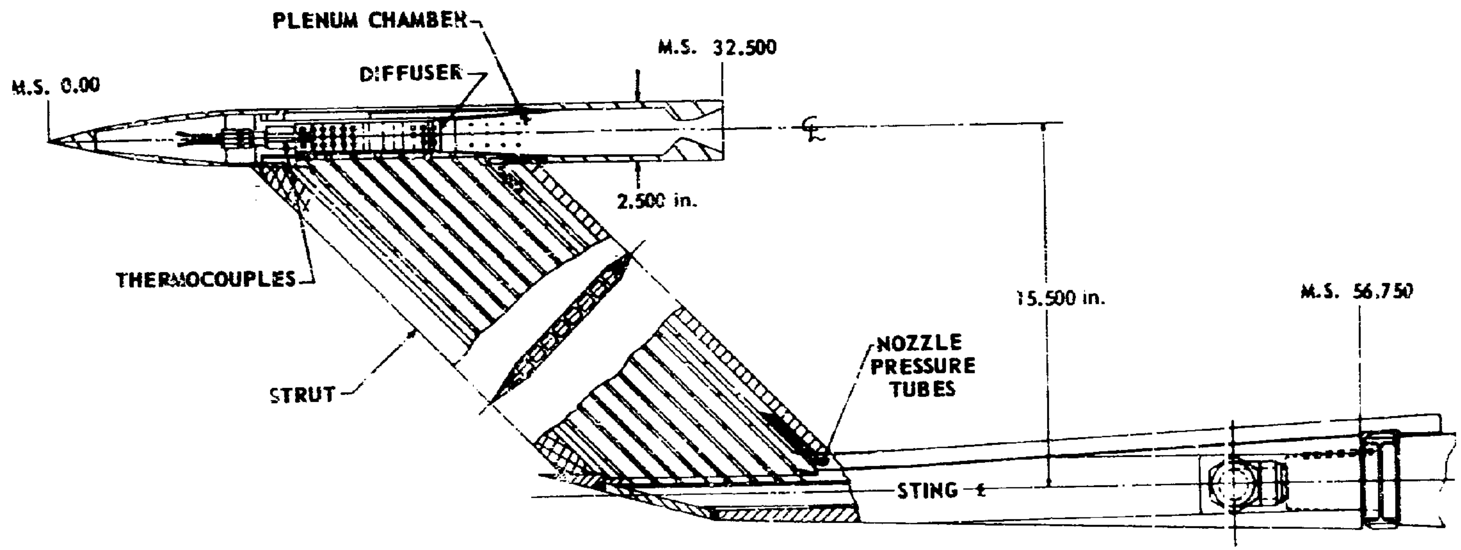


Figure 6. Strut Mounted Model

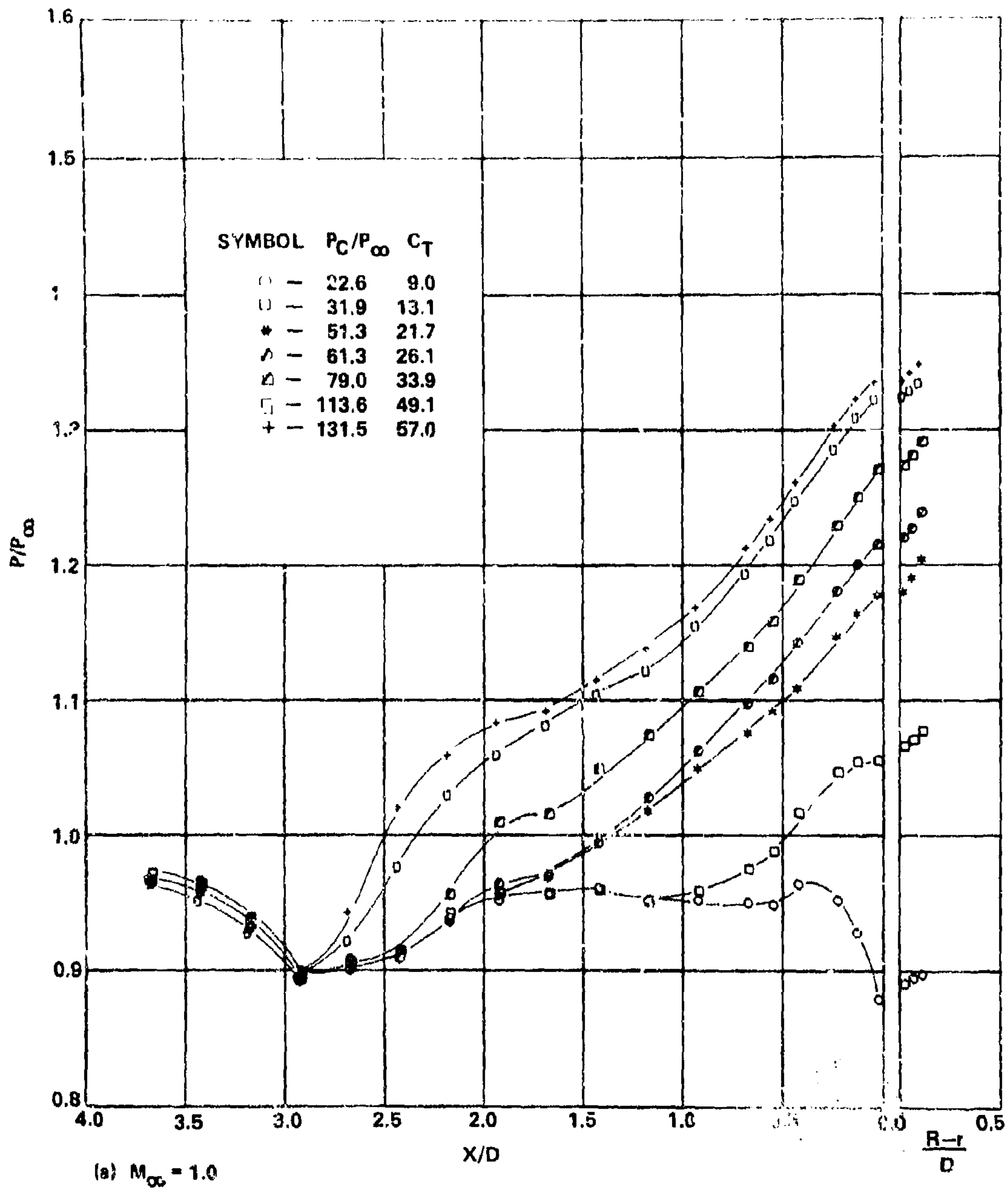
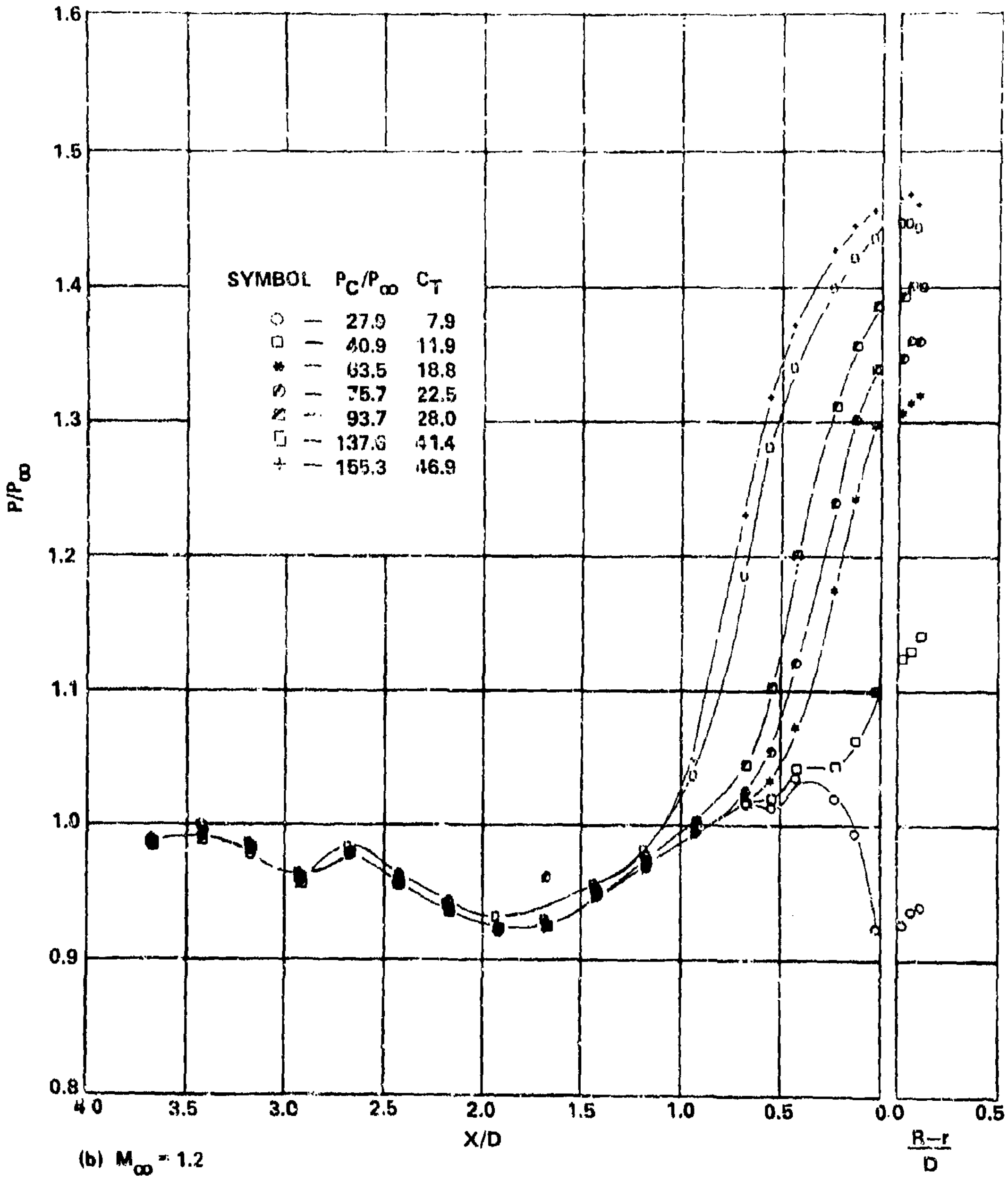


Figure 7. Effect of Thrust Level on Model Afterbody and Base Pressure Distribution, Cylindrical Body, $M_j = 2.7$, $\theta_N = 20$ deg, $D_N/D_B = 0.8$, $\alpha \approx 0$ deg



(b) $M_\infty = 1.2$

Figure 7. Concluded

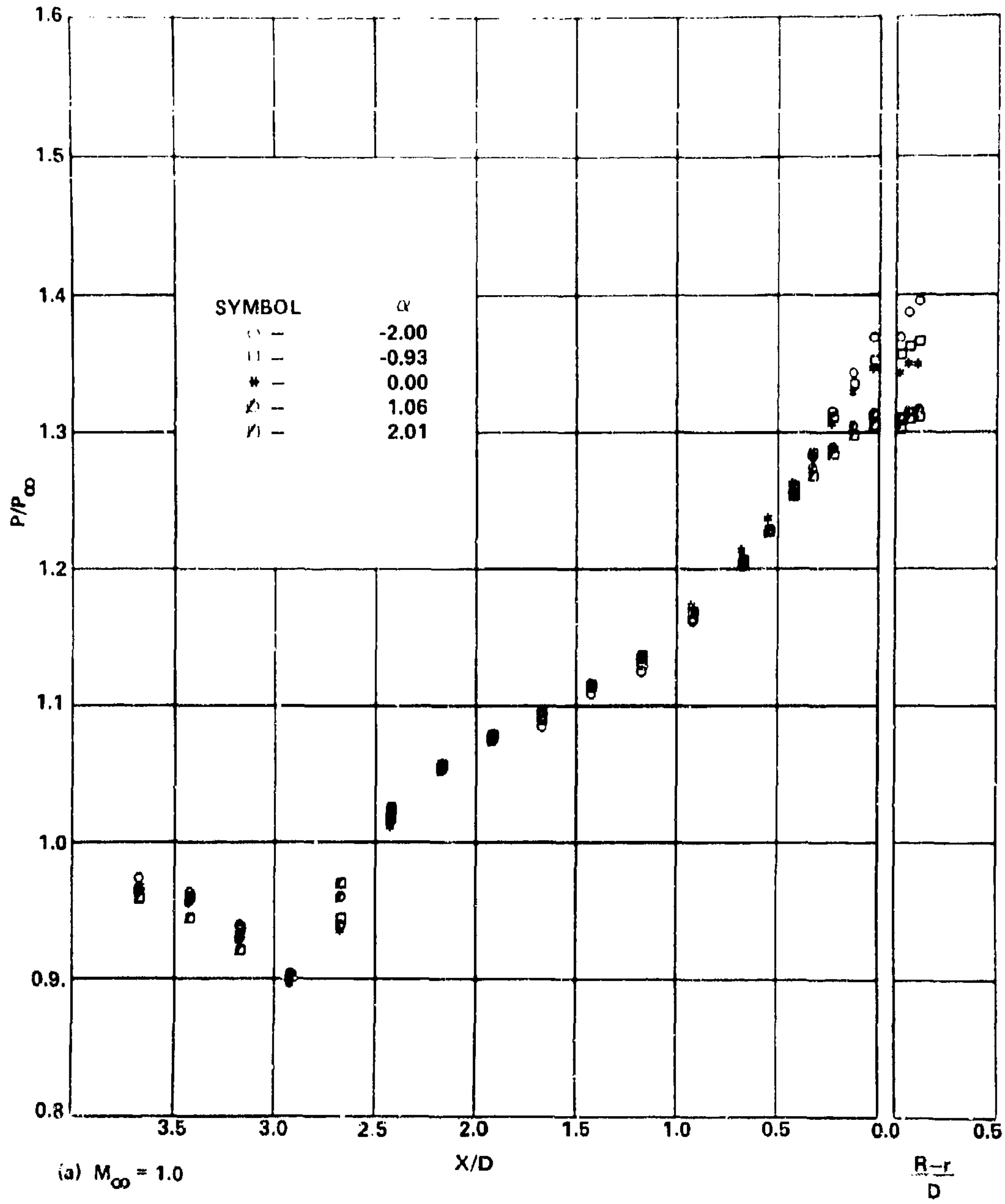


Figure 8. Effect of Model Angle of Attack on Pressure Distribution at a High Level of Thrust, Cylindrical Body, $M_j = 2.7$, $\theta_N = 20$ deg, $D_N/D_B = 0.8$, $P_c/P_\infty = 128.3$

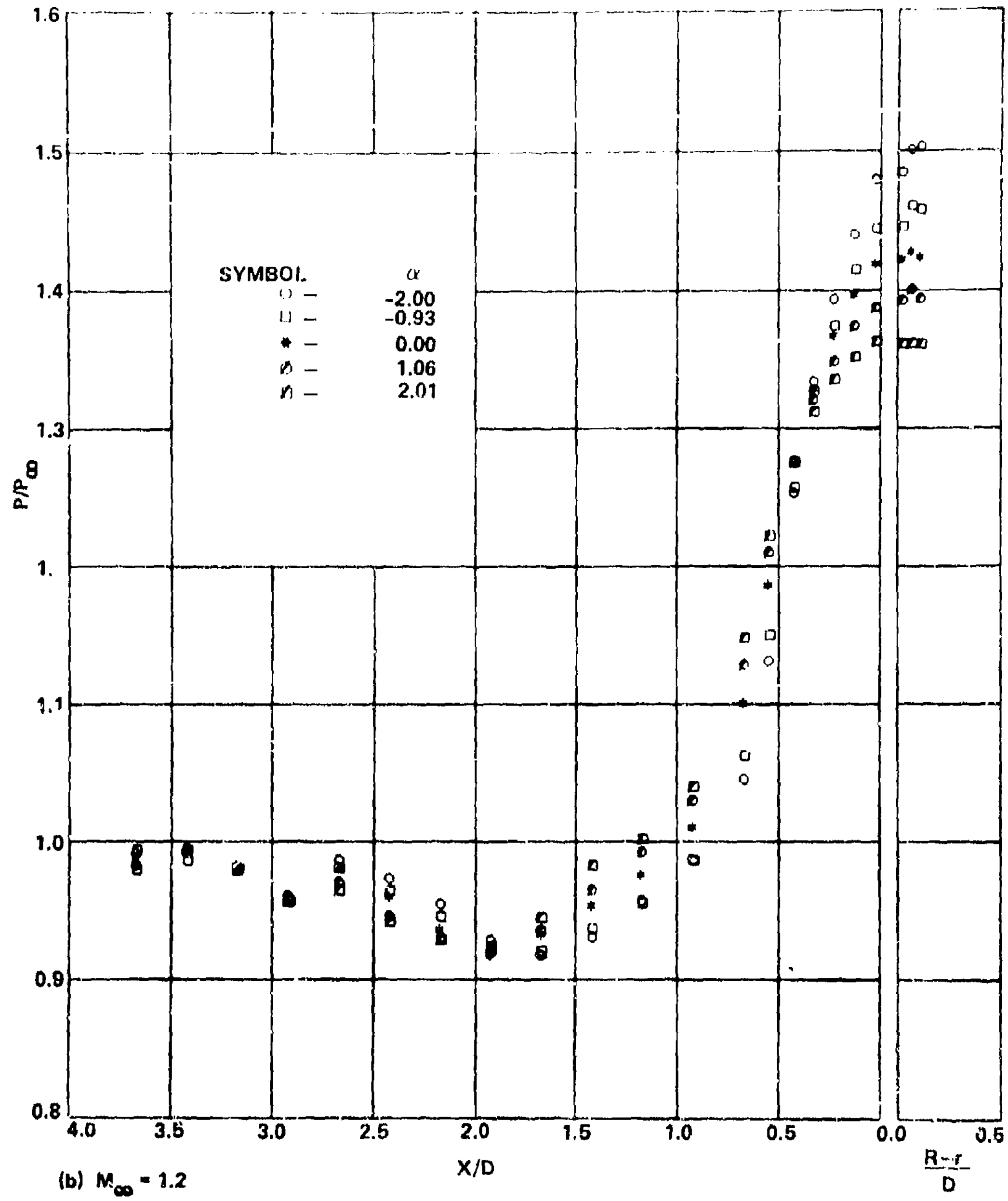


Figure 8. Concluded

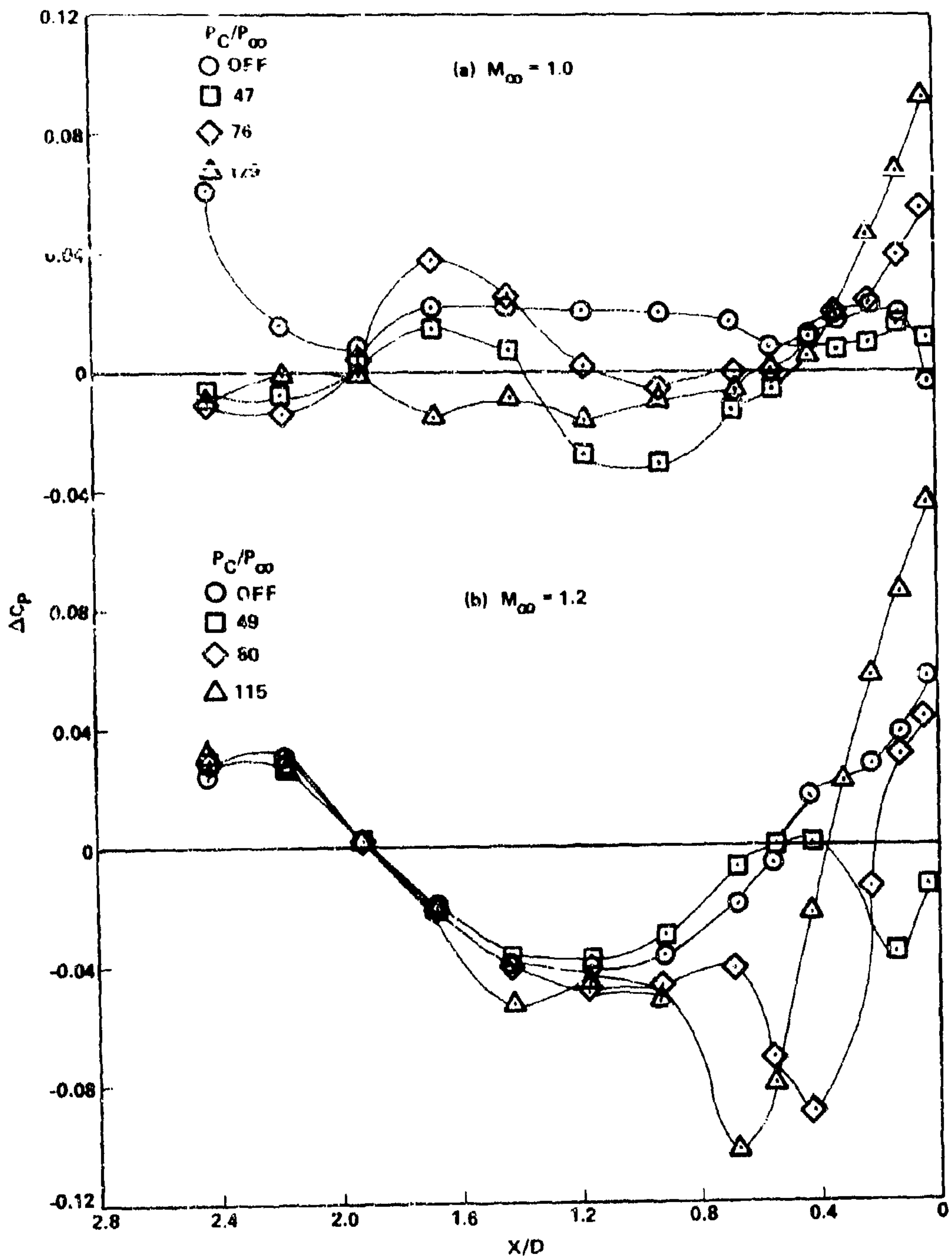


Figure 9. Loading Distribution on Afterbody Vertical Centerline Plane at Various Levels of Thrust

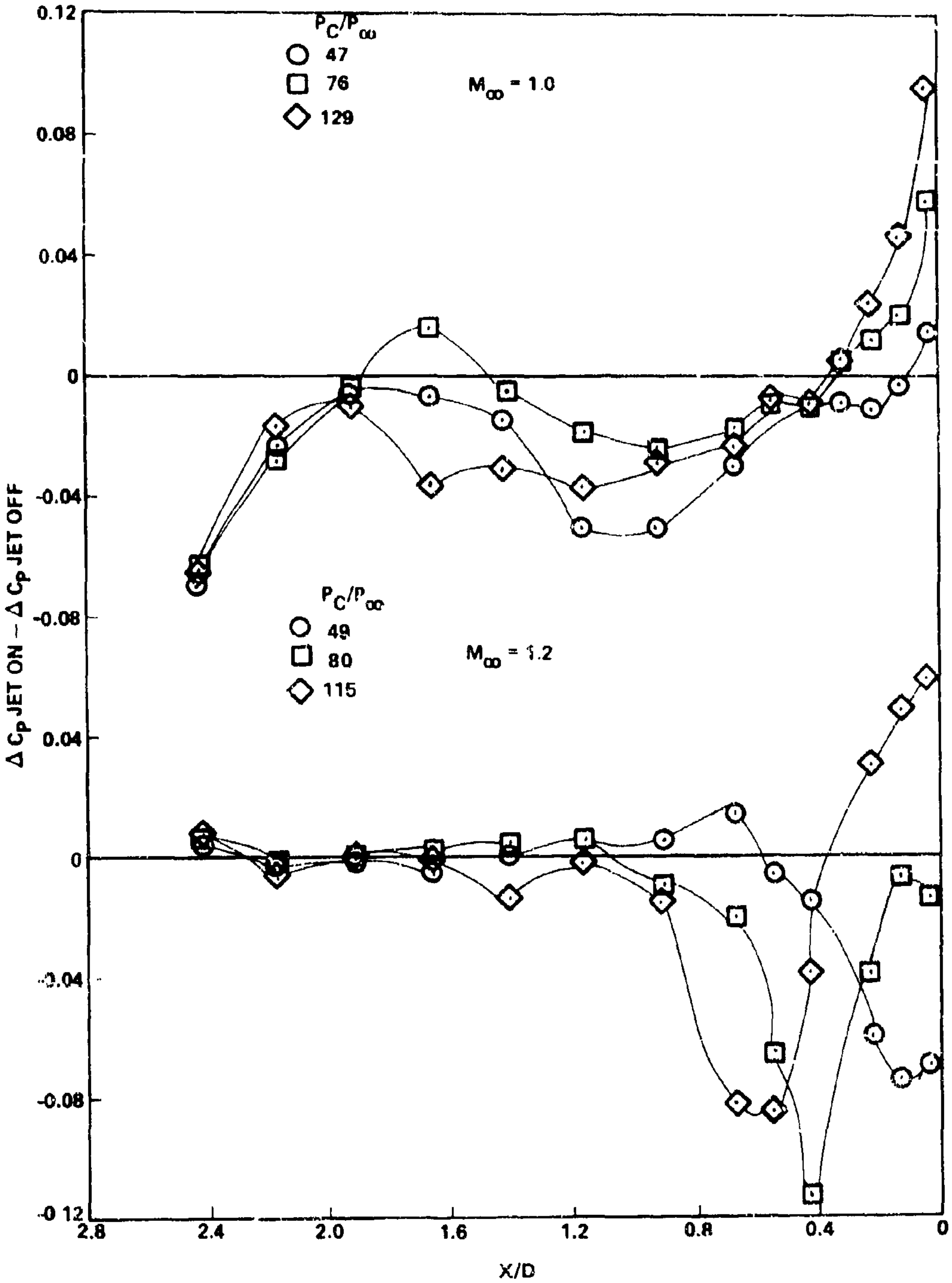


Figure 10. Jet Effects on Loading Distribution on Afterbody Vertical Centerline Plane

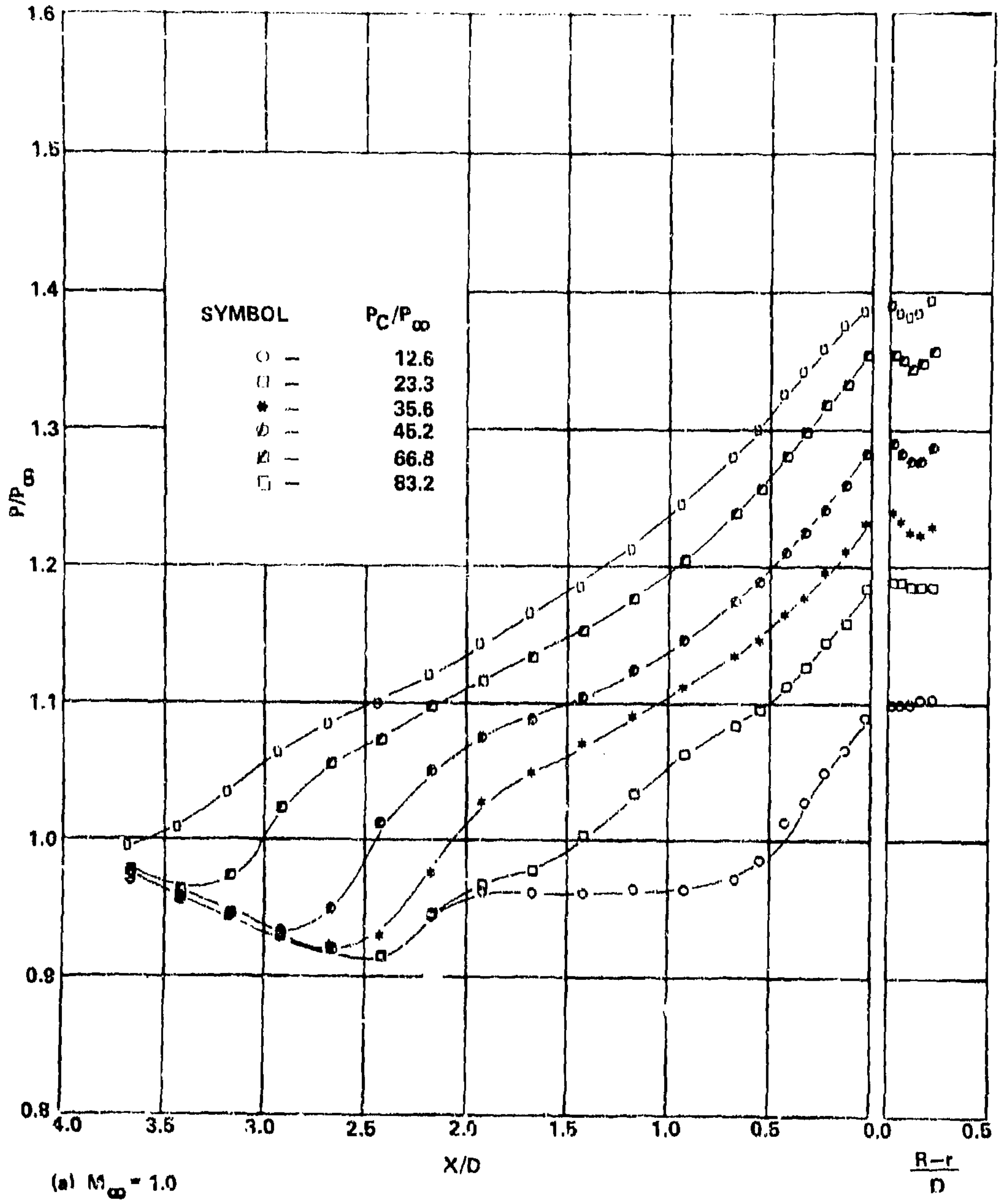
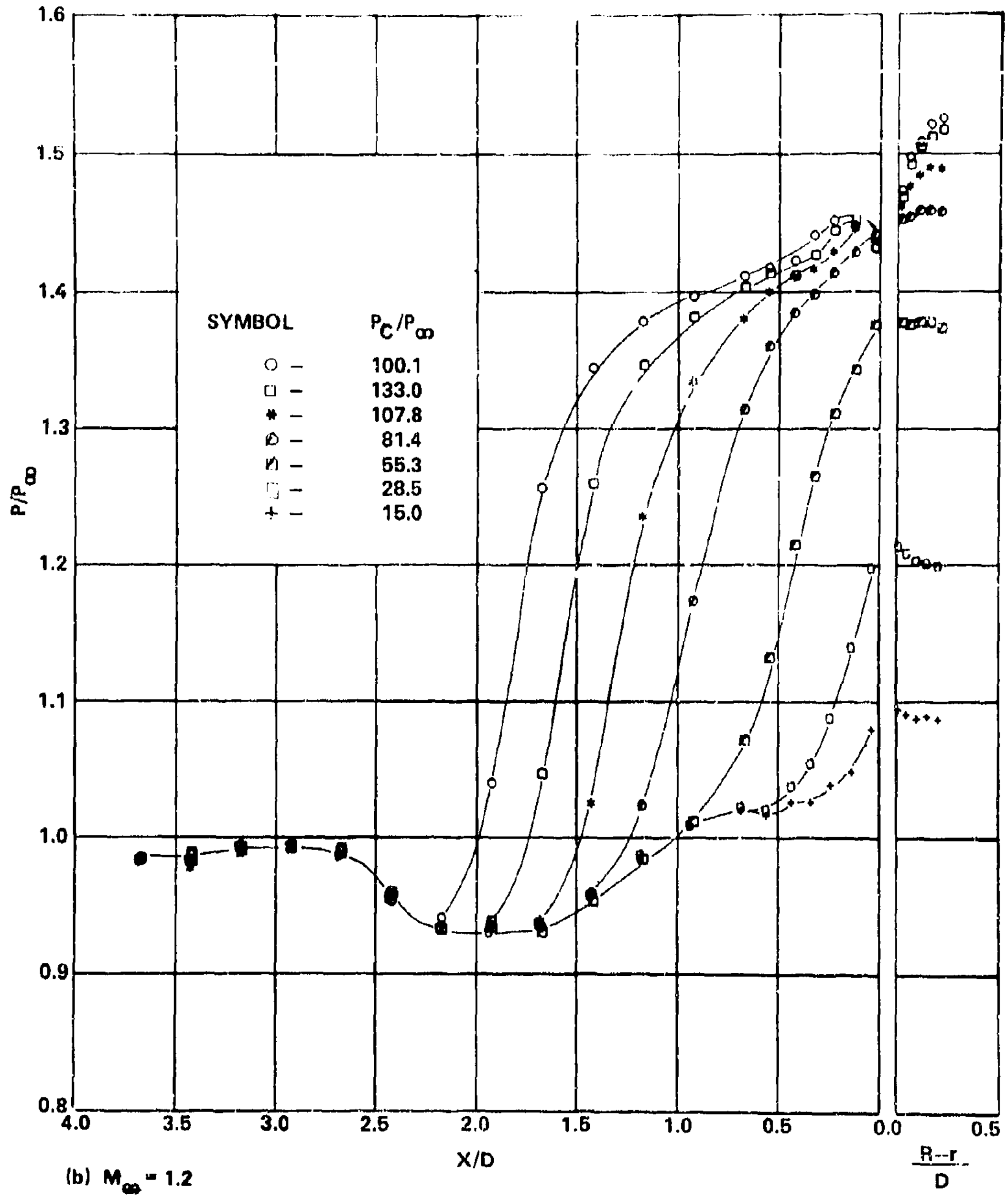


Figure 11. Effect of Thrust Variation Simulated by Normal Jets on Model Pressure Distribution, Cylindrical Body, $\alpha = 0$ deg, $X_p/D = 0.996$



(b) $M_\infty = 1.2$

Figure 11. Concluded

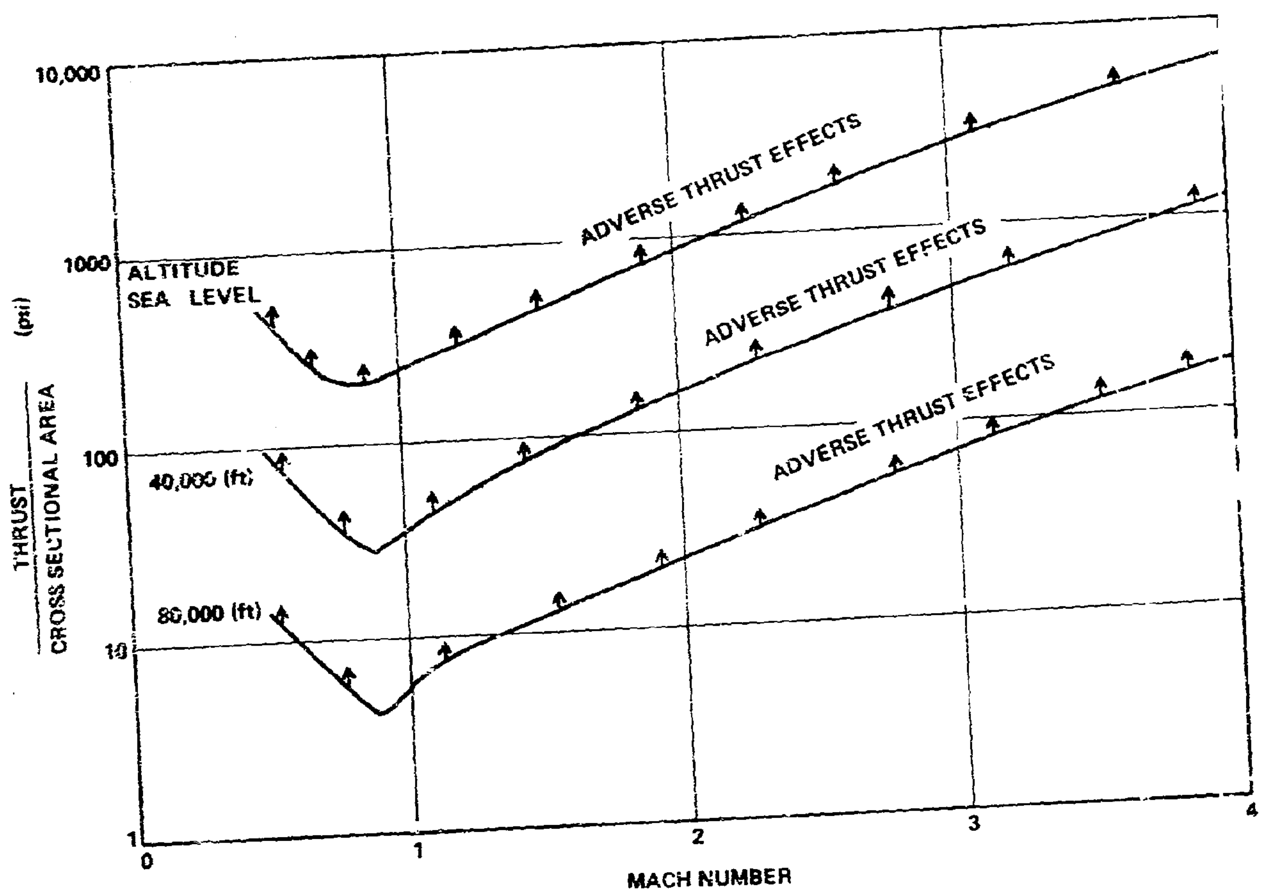


Figure 12. Estimation of Onset of Adverse Thrust Effects on Typical Missile Configurations

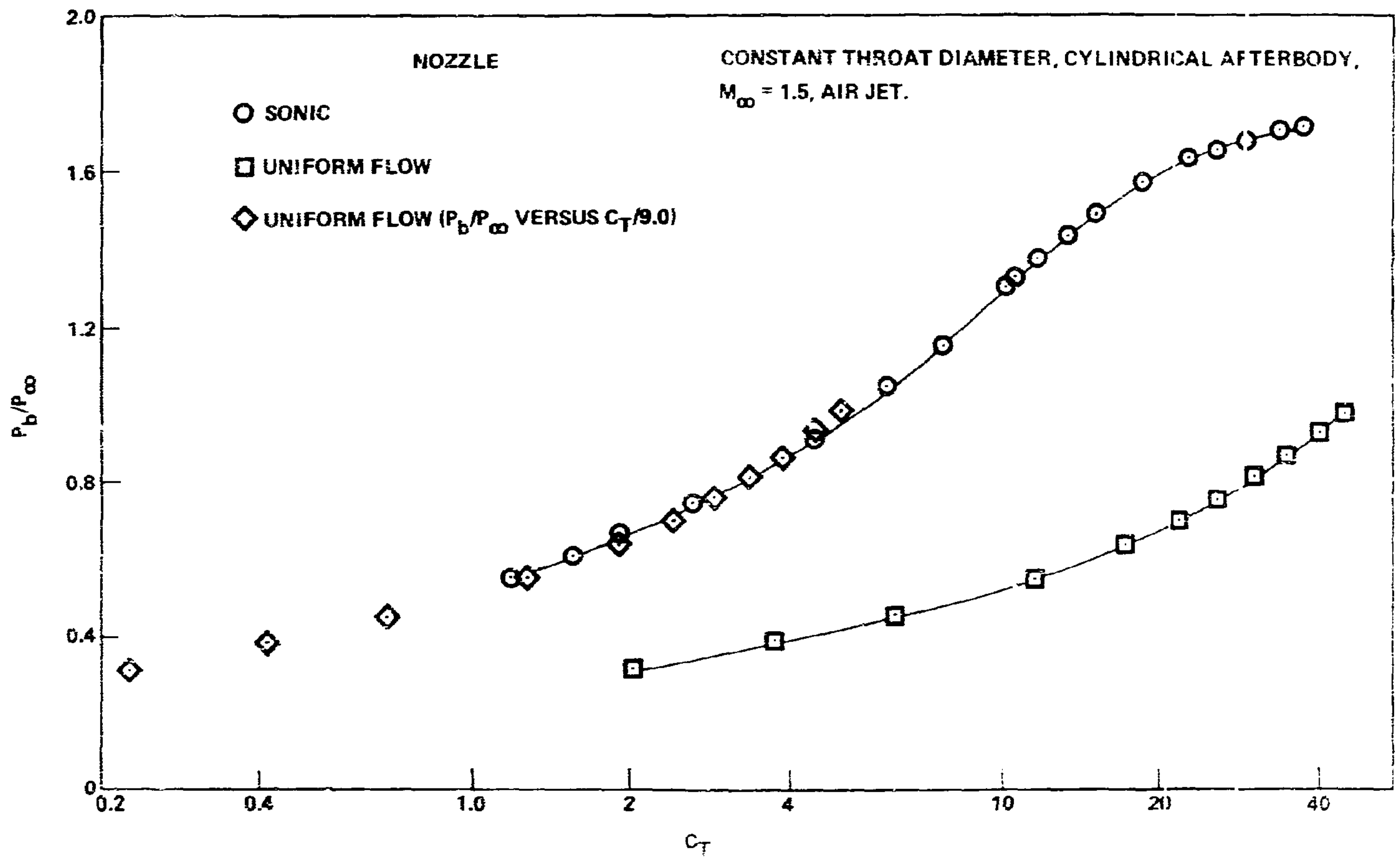


Figure 13. Comparison of Thrust Effects on Base Pressure of a Sonic Nozzle and a Uniform Flow Nozzle (M_j = 2.7)

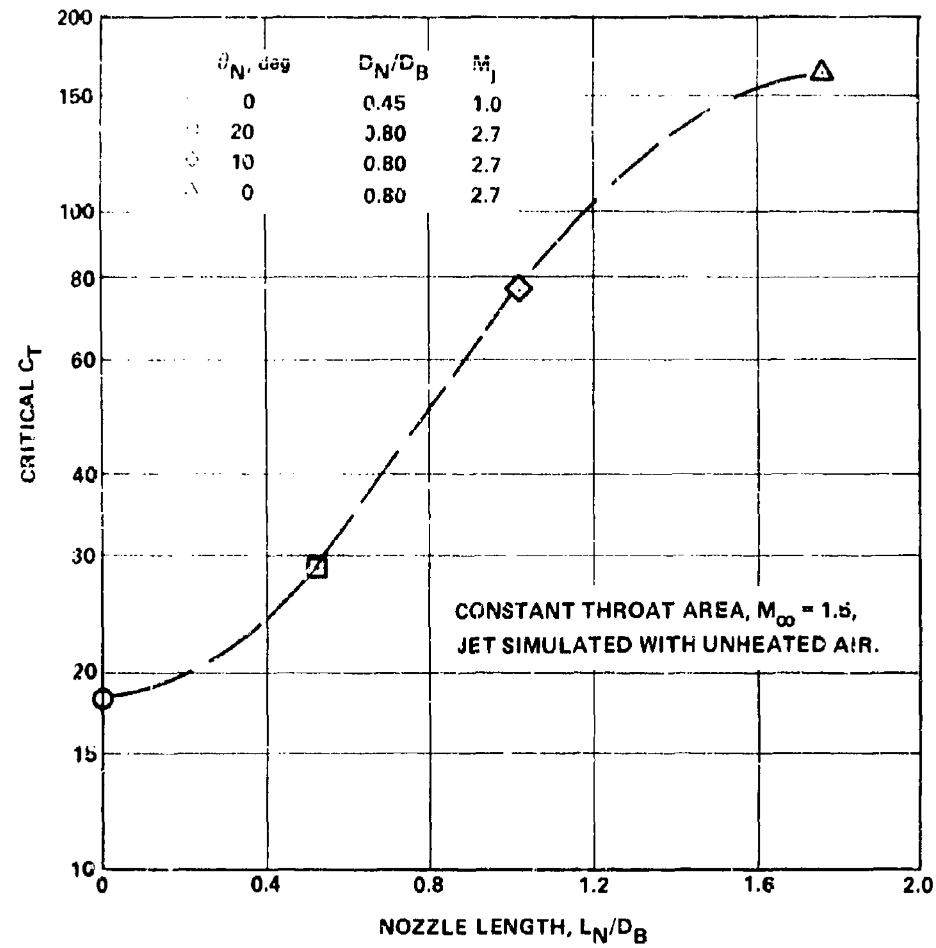


Figure 14. Effect of Nozzle Length on Delaying Onset of Adverse Plume Effects

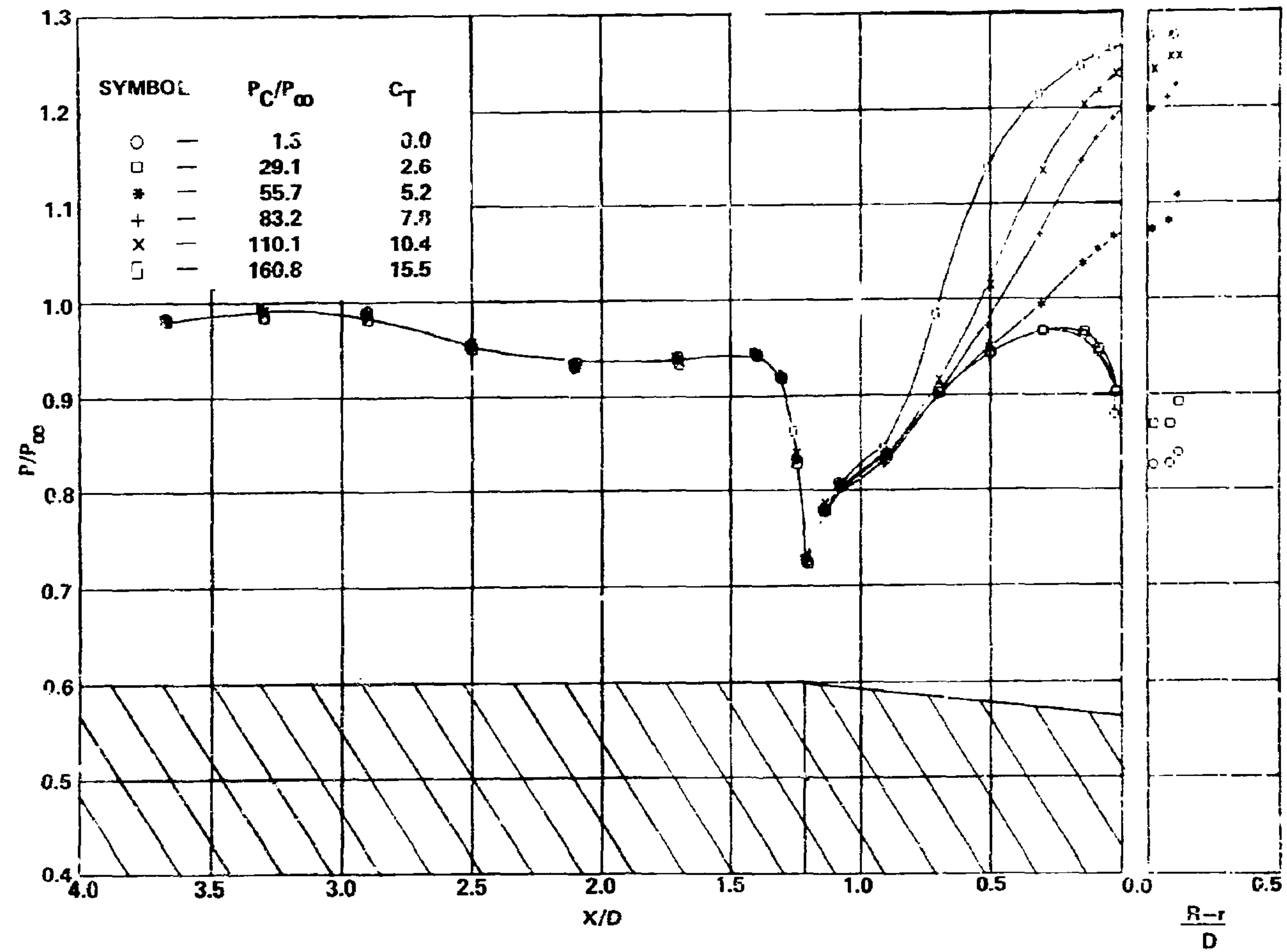


Figure 15. Thrust Effects on Pressure Distribution of Various Boattailed Afterbodies at $M_\infty = 1.2$

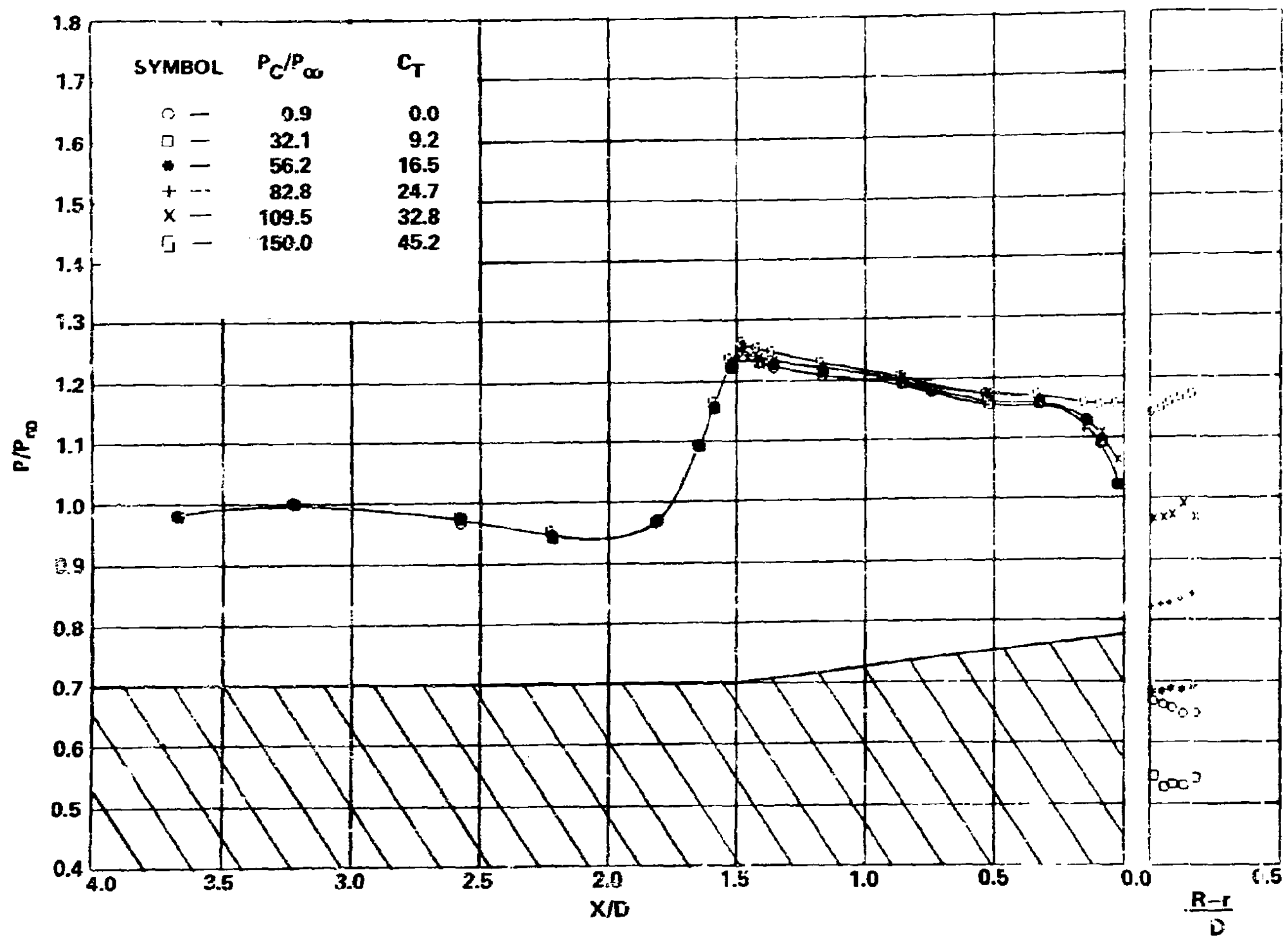


Figure 16. Thrust Effects on Pressure Distribution of Various Flared Afterbodies at $M_\infty = 1.2$

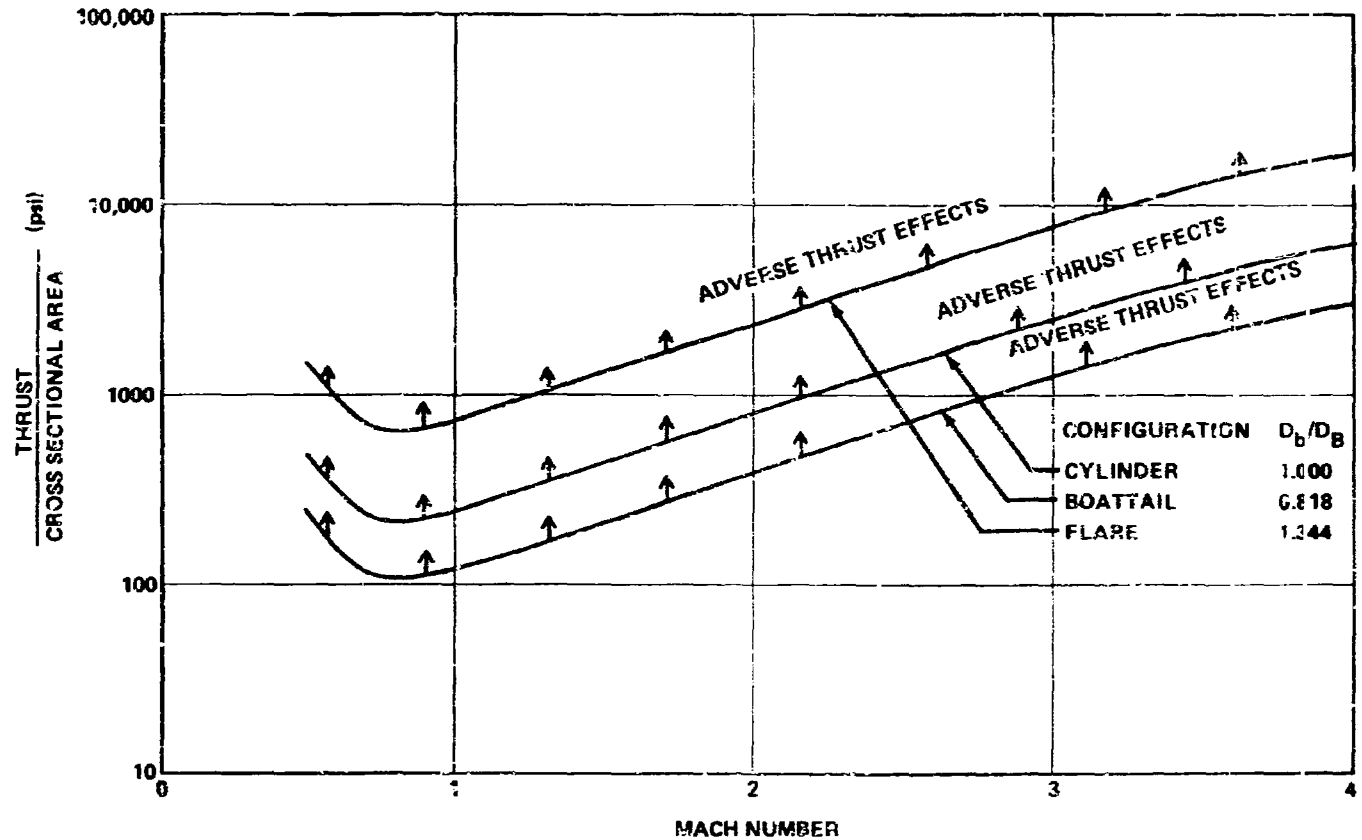


Figure 17. Effect of Afterbody Geometry on Onset of Adverse Thrust Effects (Sea Level)

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